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MATERIAL ALLOWABLES FOR HIGH CYCLE FATIGUE IN GAS TURBINE ENGINES

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SUMMARY

HCF failures in materials used in both static and rotating components of gas turbine engines have often been found to be attributable to fatigue loading on materials which have sustained some type of damage. Damage can be present from initial material or manufacturing defects, or can develop during service operation. In-service damage, while not catastrophic by itself, can degrade the HCF resistance of the material below that for which it was designed. Three major sources of in-service damage which can alter the HCF capability individually or in conjunction with one another are low cycle fatigue (LCF), foreign object damage (FOD), and contact fatigue. Other types of damage include creep, corrosion and thermal fatigue. The present design methodology is highly empirical and relies heavily on service experience to establish material allowable knockdown factors for each type of damage. To reduce HCF failures, the U.S. Air Force is developing a damage tolerant approach which addresses these issues in a less empirical manner. The effects of damage on HCF capability and a discussion of the material allowables under HCF are presented.

1. INTRODUCTION

The high incidence of HCF related failures over the past several years in U.S. Air Force gas turbine engines, combined with the substantial maintenance costs and potential detrimental effects on operational readiness, have led the Air Force to re-evaluate the design and life management procedures for HCF. In attempting to assess the root cause of HCF failures and find methods for reducing the incidence of such failures, the relatively empirical nature of the procedures now in place becomes abundantly clear. Further, the lack of detailed information on vibratory loading and dynamic response of components as well as material capability under HCF, particularly in the presence of initial or in-service damage, makes anything but a highly empirical approach impractical at this time. To address these shortcomings, the U.S. Air Force initiated a National High Cycle Fatigue Program

to develop a technology base for implementation of damage tolerance procedures for HCF in gas turbine engines. This paper focuses on the material capability aspects of the damage tolerant approach for design and life management of components subjected to HCF.

2. DAMAGE TOLERANCE

The natural tendency in the implementation of a "damage tolerant" approach to fatigue would be to relate remaining life based on predictions of crack propagation rate to inspectable flaw size. In LCF, this has been shown to work well, and such an approach was adapted by the U.S. Air Force in 1984 as part of the ENSIP Specification [1]. For HCF, direct application of such an approach cannot work for "pure" HCF because required inspection sizes are well below the state-of-the-art in non-destructive inspection (NDI) and the number of cycles in HCF is extremely large because of the high frequencies involved. Whereas LCF involves early crack initiation and a long propagation life as a fraction of total life, pure HCF damage is rarely observed in service or even in the laboratory and occurs only very late in life. It is therefore impractical to apply the damage tolerant approach as used for LCF to pure HCF. While considerable research is being conducted at the present time to identify and detect HCF damage in the early stages of total fatigue life, damage tolerance seems out of the question at present for HCF. However, the problems which arise in the field are generally not related to the lack of knowledge of material capability under pure HCF. Rather, the problems fall into two main categories. First, and foremost, is the existence of vibratory stresses from unexpected drivers and structural responses which exceed the material capability as determined from laboratory specimen and sub-component tests. Design allowables are normally obtained on material which is representative of that used in service including all aspects of processing and surface treatment and are often represented as points on a Haigh or "Modified Goodman diagram". (This point is qualified in the following paragraph.) The second category involves the

introduction of damage into the material during production or during service usage. The three most common forms of damage, either alone or in combination, are LCF cracking, foreign object damage (FOD), and contact fatigue. To account for this damage, or to design for pure HCF, the concept of a threshold below which HCF will not occur is necessary because of the potentially large number of HCF cycles which can occur over short service intervals. This is due to the high frequency of many vibrational modes, often extending into the KHz regime. In fact, current design for HCF through the use of a Haigh diagram seeks to identify maximum allowable vibratory stresses so that HCF will not occur in a component during its lifetime. The current ENSIP specification requires this HCF limit to correspond to 10^9 cycles in non-ferrous metals, a number which is hard to achieve in service and even harder to reproduce in a laboratory setting. Consider that a material subjected to a frequency of 1 KHz requires nearly 300 hours to accumulate 10^9 cycles.

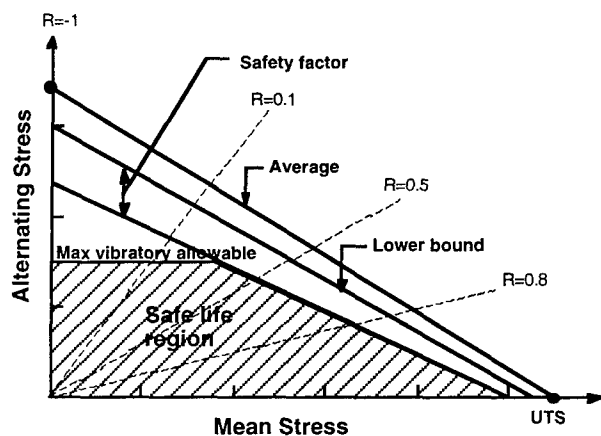


Fig. 1 Constant life diagram.

3. HCF MATERIAL ALLOWABLES

The diagram most used for design purposes in HCF is a constant life diagram as illustrated in Fig. 1, where available data are plotted as alternating stress as a function of mean stress for a constant design life, usually 10^7 or higher. This diagram, which should correctly be called a Haigh diagram, is commonly and incorrectly referred to as a Goodman diagram or a Modified Goodman diagram [2]. In the absence of data at a number of values of mean stress, it is often constructed by connecting a straight line from the data point corresponding to fully reversed loading, $R=-1$, with the ultimate tensile strength (UTS) of the material. Alternatively, the yield stress is used as the point on the mean stress axis. Data at $R=-1$ can be obtained readily from a number of

techniques using shaker tables to vibrate specimens or components about a zero mean stress, while data at other values of mean stress are often more difficult to obtain, particularly at high frequencies. Alternatives to the straight line approximation in Fig. 2 involve the use of various curves or equations going through the yield stress or UTS point on the x-axis, or through actual data if available, to represent the average behavior. Scatter in the data can be handled by statistical analysis which establishes a lower bound for the data. On top of this, a factor of safety for vibratory stress can be included to account for the somewhat indeterminate nature of vibrations, particularly those of a transient type. Finally, design practices or specifications may limit the allowable vibratory stress to be below some established maximum value, independent of the magnitude of the mean stress. The safe life region, considering all of these factors, is shown shaded in Fig. 1. What this region provides, therefore, is an allowable threshold vibratory stress as a function of mean stress, the latter being fairly well defined because it is closely related to the rotational speed of the engine. If the vibratory stress is maintained within the allowable region on the Haigh diagram, there should be no failure due to HCF and, further, no periodic inspection required for HCF. Provided that the maximum number of vibratory cycles experienced in service does not exceed the number for which the Haigh diagram is established, 10^9 for example, then such a design procedure is one of "infinite" life requiring no periodic inspection.

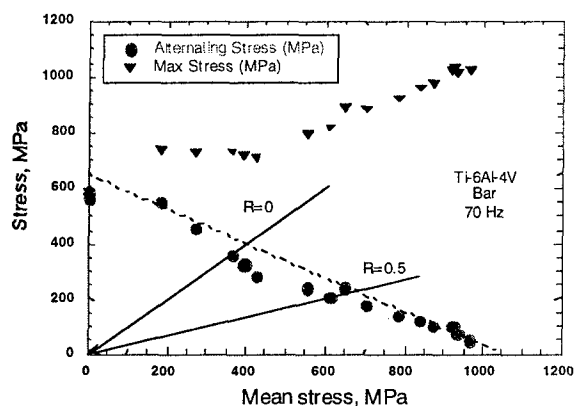


Fig. 2 Haigh diagram for Ti-6Al-4V bar.

There are some pitfalls in the use of a Haigh diagram in design, particularly when basing it only on data at $R=-1$. For example, Fig. 2 shows such a diagram for Ti-6Al-4V hot rolled bar where it can be seen that the straight line for alternating stress does only a fair job of representing the data. In addition to the alternating stress, the peak or

maximum stress is also shown. For high values of mean stress, the maximum stress is quite high, approaching the static ultimate stress of 1030 MPa for this material. Recent research on fatigue life at high mean stresses [3] has shown that at high mean stress, the fracture mode changes from one of fatigue to one of creep. Thus, in the creep regime, consideration should be given to the amount of time during which such vibrations occur, not only to the number of cycles.

Allowable vibratory stresses, while very low in this region, should also be supplemented with consideration of maximum stresses. It is for these reasons that designers shy away from the high mean stress regime, often for reasons that cannot be quantified.

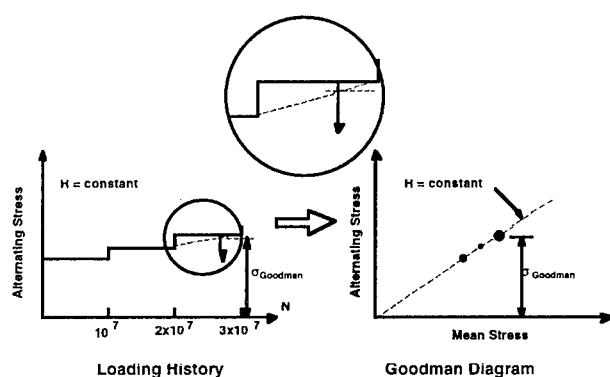


Fig. 3 Schematic of step-loading procedure.

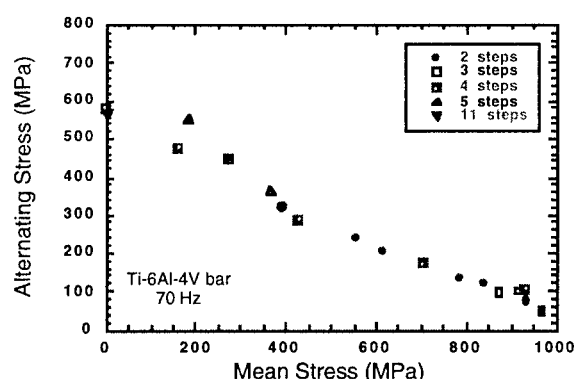


Fig. 4 Haigh diagram illustrating effect of number of steps on fatigue limit.

3.1 Obtaining material allowable data

One of the main concerns in establishing material allowables for HCF is the sparse amount of data available and the time necessary to establish data points for fatigue limits at 10^7 cycles or beyond. The conventional method for establishing a fatigue limit is to obtain S-N data over a range of stresses and to fit the data with some type of curve or straight line approximation. For a fatigue limit at 10^7 cycles, for example, this

requires a number of fatigue tests, some of which will be in excess of 10^7 cycles. This is both time consuming and costly. One method for reducing the time is to use a high frequency test machine such as one of those which have appeared on the market within the last several years. In addition, the use of a rapid test technique such as one developed by Maxwell and Nicholas [4] involving step loading can save considerable testing time. It has been shown that such a technique provides data for the fatigue limit which are consistent with those obtained in the conventional S-N manner [4, 5]. The approach is illustrated schematically in Fig. 3 where a constant amplitude fatigue load is applied for a number of cycles corresponding to the number for which the fatigue limit is desired. If no failure occurs within this block of loading, the stress is raised and a second block is applied. The procedure is repeated until failure occurs within a block and the fatigue limit is established by a simple interpolation scheme involving the load levels of the final and prior blocks and the number of cycles in the final block. Data for a Haigh diagram obtained in this manner are shown in Fig. 4 where the number of blocks used for each data point is also indicated. It can be seen that there is no systematic trend for the value of the fatigue limit with the number of blocks. This is just one illustration of many that have shown that the so-called "coaxing" effect, where loading below the fatigue limit strengthens the material, does not exist in the Ti-6Al-4V material tested.

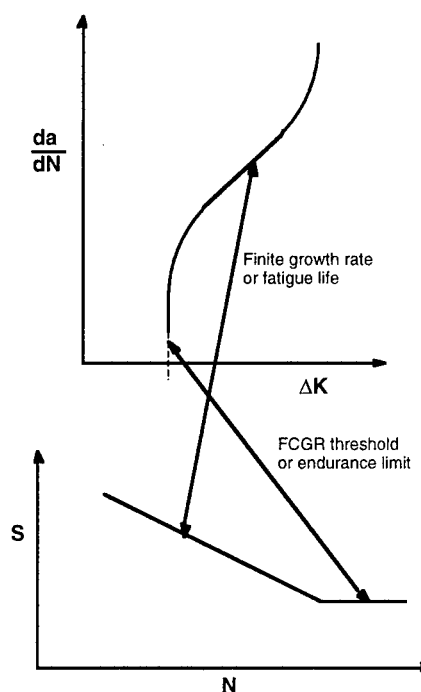


Fig. 5 Schematic illustrating threshold concept in fatigue and crack growth.

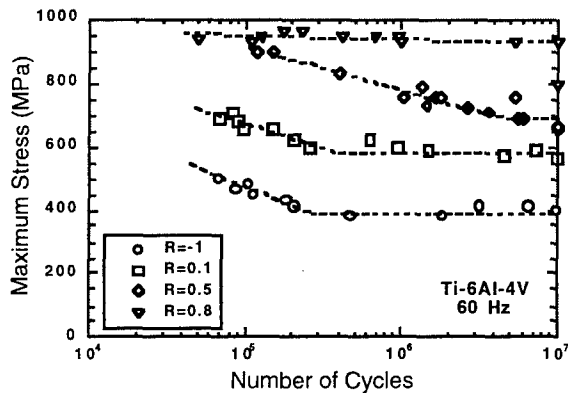


Fig. 6 S-N data at different values of R.

3.2 Threshold concept for HCF

Because of the large number of HCF cycles that may occur in service due to high frequency vibrations in a component, a threshold concept is necessary to insure structural integrity. Whether this threshold involves crack growth rates below some operational threshold, or the use of a fatigue limit corresponding to a large but fixed number of cycles, the concepts involve "infinite life," at least within the number of cycles that may be assumed to occur during the lifetime of a component. These could be either from steady state vibrations or from transient phenomena and would correspond to a different number of total expected cycles in general. The infinite life concept is illustrated schematically in Fig. 5 for crack growth and fatigue. In crack growth, a pre-existing or developed crack should not grow at a rate beyond some threshold rate so that crack extension can be neglected during the expected life of the material. Similarly, for a material without a crack, the stress level has to be maintained below a fatigue limit such that fatigue failure does not occur within an expected number of cycles. If the number of expected cycles can be established, and the crack growth rate and S-N curves can be estimated, then a threshold growth rate and a fatigue limit can be determined which are consistent with each other and account for "infinite" life for the expected number of cycles. In establishing such limits for fatigue, the shape of the S-N curve has to be taken into consideration. As an example, Fig. 6 shows S-N data for Ti-6Al-4V at several values of stress ratio, R. It is to be noted that the slopes of the curves are different, and the transition point where the curves become nearly flat differs depending on the value of R. Therefore, stress ratio becomes an important parameter in establishing the fatigue limit, just as is shown in the Haigh diagram where mean stress is used as the variable to establish allowable alternating stress.

4. DAMAGE CONSIDERATIONS

While methods appear to be available to quantify the fatigue limit of a material subjected to HCF, and to establish a threshold for a crack of an inspectable size, there are still issues remaining over how severe is the damage induced by LCF, FOD or contact fatigue and what material allowables should be used to account for such damage. Other modes of service-induced damage, such as creep, thermo-mechanical fatigue, corrosion, erosion, and initial damage from manufacturing and machining, must also be taken into account in establishing material capability and inspection intervals.

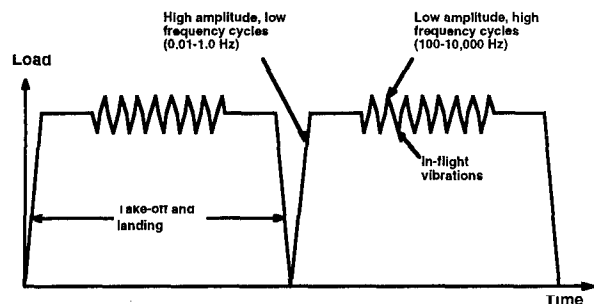


Fig. 7 Schematic of LCF and HCF.

4.1 LCF/HCF interactions

A representative turbine engine spectrum, shown schematically in Fig. 7, contains the simplest version of low and high cycle fatigue loading. The LCF loads or major cycles are those which represent takeoff and landing conditions whilst the HCF or minor cycles represent vibrations during flight. Of concern is what happens if cracks develop in a component due to LCF and then that component experiences HCF. It is important to know how the LCF degrades the fatigue limit, even when the LCF will not cause catastrophic failure by itself. Some preliminary experiments have shown, so far, that this may not be a major issue within the narrow limits of the parameters used in the investigation. Results are presented in Fig. 8 for the fatigue limit on Ti-6Al-4V plate which has been subjected to prior LCF for some fraction of the LCF life which is approximately 10^4 cycles at $R=0.1$. Under these conditions there is only a slight loss in fatigue limit stress up to 75% of LCF life. Note, however, that LCF life is itself a statistical variable. Much more work has to be conducted to establish LCF damage parameters for assessing remaining HCF life.

Another concern involving LCF is the effect of overloads and underloads on the subsequent HCF fatigue limit as illustrated schematically in Fig. 9.

When the peak stresses or stress ratio, R , of the HCF is different than that of the LCF, it is known from the literature that these prior underloads and overloads can accelerate or retard, respectively, a growing crack in a material compared to constant amplitude crack growth rates. What is not known, however, is whether or not such variable amplitude loading has any effect on the fatigue limit when there is no crack present or in the short crack regime where cracks exist but are too small to detect. This is another area where further work is needed.

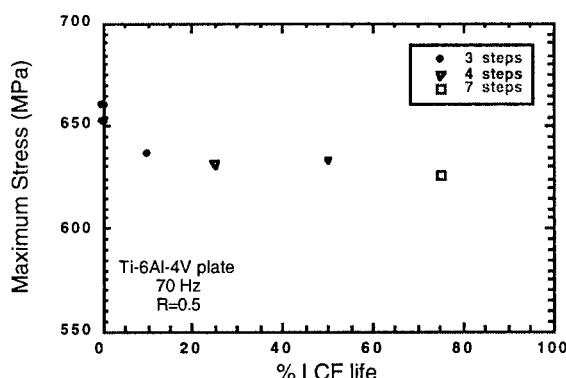


Fig. 8 HCF fatigue limit after applying LCF.

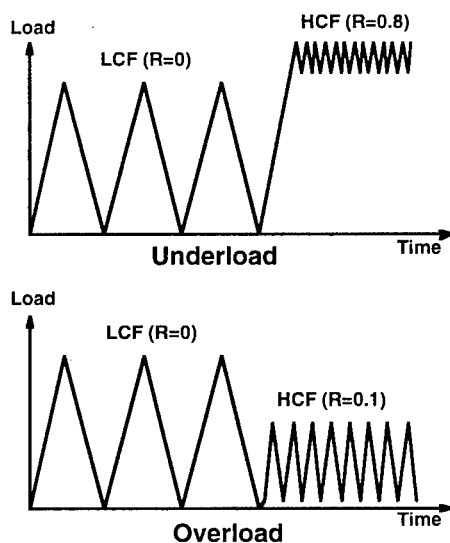


Fig. 9 Overload and underload considerations.

Another aspect to be considered in establishing fatigue limits for HCF is the frequency of loading in the laboratory and the frequencies encountered in vibrating components. Resonant and forced vibrations in engine components can often be in the kilohertz regime whereas laboratory testing is mostly conducted at 100 Hz or less because of equipment limitations. There have been

developments over the last several years which have resulted in fatigue testing capability at frequencies up to 2 KHz, and ultrasonic resonant machines have been in existence for several years which have the capability to test typically at 20 KHz. These machines allow for testing at more realistic frequencies for applications and, more important, allow for data to be generated at larger numbers of cycles to failure than conventional machines. The data in Fig. 10 illustrate the capability to establish a fatigue limit corresponding to 10^8 or 10^9 cycles. In this particular case, there is little or no degradation of the fatigue limit when going to such a large number of cycles, but some recent experiments conducted at 20 KHz indicate that the fatigue limit may decrease for such a large number of cycles [6]. Again, this is an area where more work is required.

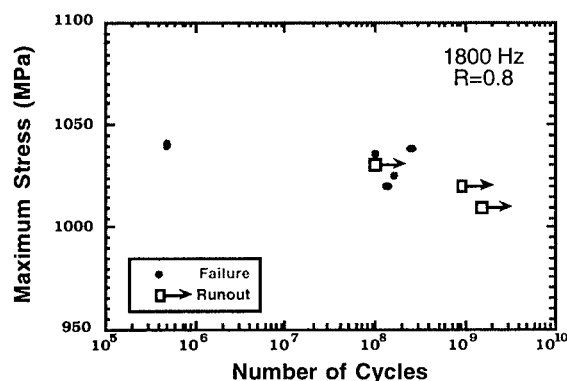


Fig. 10 S-N behavior of Ti-6Al-4V at 1800 Hz.

4.2 FOD and notches

Foreign objects impacting leading edges of rotating blades or static structures can produce damage in the form of notches or tears as shown schematically in Fig. 11. In addition to a geometric discontinuity which may look like a notch, there are residual stresses or strains at the root of the damaging notch from the impact which causes FOD. Whilst data exist on effects of notches on the S-N behavior of a material, there are fewer data on the effects of FOD and hardly any information on any change in the fatigue limit for a material which has been subjected to prestrain or damage due to FOD. Early data on titanium indicates that a tensile prestrain may increase the fatigue limit [7], but recent unpublished results in our laboratory indicate a possible decrease. The effect of precompression is also being investigated.

Attempts have been made to quantify FOD damage in the form of an equivalent K_t , but

relating that to actual material behavior is difficult. First, it is difficult to establish the effective value of K_t , particularly when residual stresses are produced and when small cracks are formed at the tip of the notch. Second, there are an unlimited number of notch geometries involving combinations of depth and radius of notch which will produce the same value of K_t for a given loading condition. Third, while some data exist on the reduction of fatigue life at a given stress due to FOD, there are few data available on the reduction of the fatigue limit, particularly in the very high cycle regime. These "regions of ignorance" are shown schematically in Fig. 11 as dashed lines. Recent work has provided some quantitative results on the fatigue notch factor, K_f (unnotched fatigue limit stress/notched fatigue limit stress) for machined notches in Ti-6Al-4V. Bellows et al. [8] report values of $K_f = 1.8$ and 2.1 for $R = -1$ and $R = 0.1$ respectively using specimens with a notch having a $K_t = 2.5$ for 10^7 cycles at 60 Hz. Lanning et al. [9] report values of $K_f = 2.1, 1.8$, and 1.3 for 10^6 cycles for $R = 0.1, 0.5$ and 0.8 respectively, for $K_t = 2.8$ at 50 Hz. If the notch root radius is a measure of the fatigue resistance of the material, then a plot such as Fig. 12 would show some repeatable functional form. For very small radii, for a fixed value of K_f as shown, the value of K_f should approach unity. For a large radius, K_f should approach the value of K_t which is 2.7 for the results shown. The results shown in Fig. 12 show that whatever functional form is used must account for differences depending on stress ratio, R .

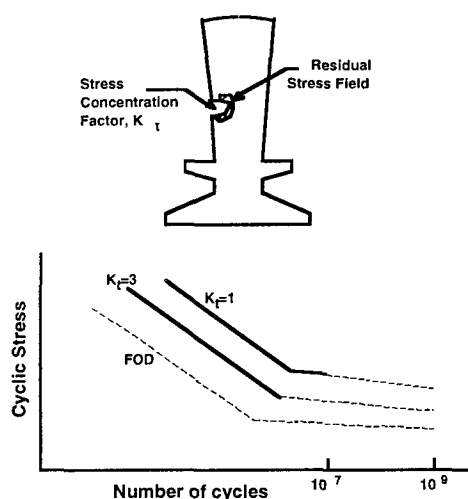


Fig. 11 Schematic of FOD concerns in design.

Data from studies of notch fatigue allow design limits for vibratory stress to be established for notches of a known K_t . But how do these relate

to the performance of a material which has suffered FOD from a particle impacting at high velocities? Results for values of the fatigue limit in Ti-6Al-4V have recently been obtained using tension specimens which have a leading edge geometry similar to a fan or compressor blade. Tests on a leading edge (LE) specimen whose LE thickness is 0.75 mm (radius = 0.38 mm) have been conducted by impacting the LE with 1 mm diam. glass spheres at a velocity of 300 m/s and at incident angles between 0° and 60° [10]. Results are shown in Fig. 13 which shows the 10^7 cycle fatigue limit for the various conditions normalized with respect to the undamaged material at 2 values of R . It can be seen that normal incidence, 0° , is the least damaging for these impacts. The worst condition is when the impact angle is around 30° although a large amount of scatter is seen in the data. It is clear that experimental and analytical methods for assessing the extent of FOD damage must consider angle of incidence as an important parameter.

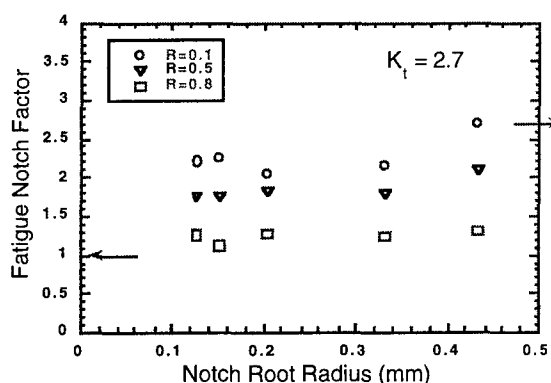


Fig. 12 Fatigue notch factor as a function of radius of notch.

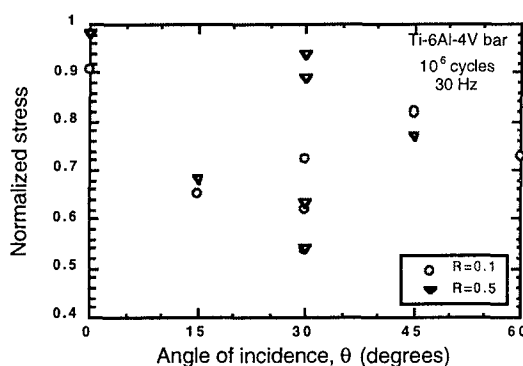


Fig. 13 Effect of incidence angle on fatigue limit of material subjected to FOD.

4.3 Contact fatigue and fretting

Contact fatigue in dovetail joints in the form of fretting is one of the most difficult and one of the

costliest problems in the U.S. Air Force related to HCF. Fretting fatigue occurs when there is small relative motion in the contact region between two surfaces. In the schematic of a dovetail, Fig. 14, it is seen that the contact region involves normal and shear loads as well as bending moments across the interface. In addition to the loads shown, there are axial stresses in both the blade and disk parallel to the contact plane. Superimposed on the loads from the steady centrifugal loading of the blade are vibratory stresses which can result from blade vibrations. Because of the nature of the stress fields in contact regions, there is always a region of relative slip near the edge of contact, shown schematically in Fig. 15. The general problem, therefore, involves normal contact forces, N , tangential contact forces, T , axial loading of the material, P , regions of stick and slip, and a relative displacement in the slip region. Depending on the magnitude of this relative motion and the stress fields produced by the steady and vibratory stresses, fretting fatigue can occur near the edges of the contact region. Whether fretting fatigue is due entirely to the relative motion, or whether the complex stress field contributes significantly to the process, is still debated. Nonetheless, laboratory experiments and field usage demonstrate that fretting fatigue can reduce the HCF material capability significantly.

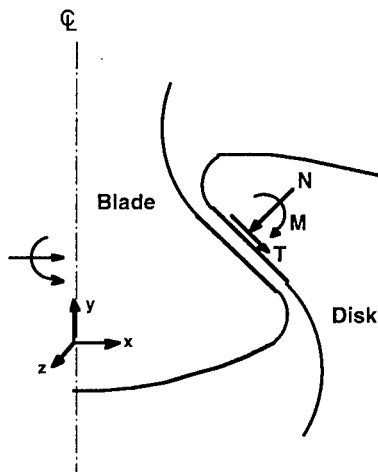


Fig. 14 Schematic of a dovetail region.

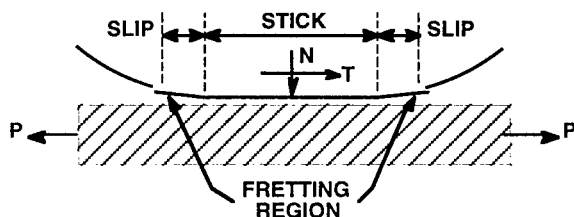


Fig. 15 Schematic of loads in contact region under fretting fatigue conditions.

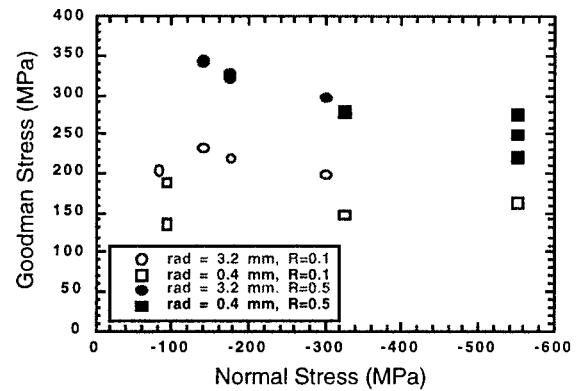


Fig. 16 Fatigue limit stresses under fretting.

Results for the fatigue limit stress corresponding to 10^7 cycles for specimens held in a fretting pad fixture [11] are presented in Fig. 16. The data shown represent the maximum stress, denoted by "Goodman stress", for tests conducted at two stress ratios using fretting pads with two different radii at the edge of contact. The data are plotted against the average normal (clamping) stress of the pad on the specimen. For comparison purposes, typical Goodman stress values for the Ti-6Al-4V used as the specimen and pad material are 600 and 825 MPa for $R=0.1$ and $R=0.5$, respectively. It can be seen from the figure that the values under fretting conditions are significantly lower than for the unfretted material. To quantify the reduction in fretting capability, an average knockdown factor (KF) is calculated as the unfretted fatigue limit stress divided by the fretting fatigue limit stress. This definition is similar to the one used for notches, K_f . Results to date conducted under limited conditions have shown that the larger contact radius produces the larger value of KF for both values of $R=0.1$ and 0.5 . Second, tests at $R=0.1$ produce a higher value of KF than those conducted at $R=0.5$. While these trends and corresponding values of KF are significant and should be taken account of in design, there appears to be no systematic change in Goodman stress with value of clamping stress over the range of clamping stresses which cover roughly a factor of six as seen in Fig. 16. The authors conclude tentatively that the normal stress may not have much affect on the relative slip length in the contact region, but clearly more work has to be done to quantify all such effects. These results show, however, that use of a single factor of safety on the allowable alternating stress in a Haigh diagram, a procedure that has been used in design more than once, is not a rational approach and may be non-conservative for some contact stress conditions if the factor of safety is obtained

empirically for one specific condition. It should be pointed out that the values for KF range from 2.6 to 4.2 for the limited range of conditions studied.

5. HCF DAMAGE TOLERANCE

The ultimate goal is to be able to design for HCF in the presence of any type of damage or service usage which degrades the properties of materials under HCF loading. The concept is illustrated in Fig. 17 which shows, schematically, some type of damage which might affect material capability. Such damage state, denoted by D, will have a design life which is some fraction of the actual life under those conditions. The damage may be a continually increasing function, such as LCF, or may be a step function such as FOD. In either case, the material would be removed from service for cause (inspection) or because the design life is reached. Just prior to removal, the material has its least resistance to HCF. A damage tolerant design should address the HCF capability under the most severe and probable damage state, shown schematically in Fig. 17 as the critical damage state. Various approaches to implementing such an approach are discussed in the following subsections.

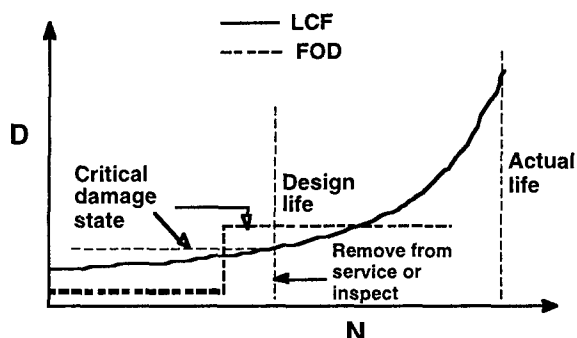


Fig. 17 Schematic of damage tolerance considerations in material allowables.

5.1 Crack growth thresholds

For damage in the form of cracks, from LCF, FOD, or fretting fatigue, the use of a fracture mechanics threshold to determine the allowable vibratory stress seems to be a promising approach for HCF, and follows the concept now being used successfully for LCF. Provided that an inspection can be made, and crack lengths measured, knowledge of the threshold for crack propagation can be used to assess the susceptibility of the material to HCF crack propagation. If the stresses are maintained below this limit, and the limit corresponds to a sufficiently low growth rate, perhaps 10^{-10} m/cycle or lower, then safe

HCF life is assured. The potential growth of such cracks under LCF, and the time interval where such growth produces a crack where HCF might occur, must also be considered. This would establish the required inspection interval. One key issue in this proposed scenario is the determination of a suitable threshold for the types of cracks which may occur in service, some of which could be quite small. Various types of loading conditions can be used to determine a threshold, most of which are for long cracks. Fig. 17 Schematic of damage tolerance considerations in material allowables.

6. CONCLUDING REMARKS

Damage tolerant approaches for HCF are still in the development stage. Whatever their final form, it seems clear that they will involve the use of a threshold concept, a criterion for a smooth or damaged material below which HCF will not occur. The criterion could be in the form of a stress or a stress intensity. From a maintenance and life extension point of view, it is important to be able to quantify the level of damage that may be present from other than HCF, such as from LCF, FOD, or fretting. This may be accomplished by inspection, analysis, probabilistics, or some combination of these. In addition, methods need to be established to predict the growth or extension of any such damage so that material capability limits are not exceeded before the next inspection or the component is removed from service.

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